# Measurement of Total Electron Content (TEC) using Virtual Reference Station (VRS) data at Ionosphere Layer

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***Abstract***— This research presents the TEC value using levelling process based on time of the day, ionosphere height and location of the receivers in Malaysia. These 3 parameters will be used for project approach. The main focus is to study the concept of VRS techniques in Malaysia and the development of TEC calculation in ionospheric area using RINEX (Receiver Independent Exchange) VRS data format which received from JUPEM (Department of Survey and Mapping Malaysia) Kuala Lumpur. The target is to implement levelling process and calculation VRS total electron content and apply the dual frequency method in mapping functions, single layer model (SLM) and modified single layer model (M-SLM) for Total Electron Content (TEC). The results show that the content of TEC in Malaysia VRS station varies between -14.7006 TECU to maximum -33.9636 TECU. The vertical TEC values are precise, accurate and without multipath, unless the multipath environment is really terrible.

***Key words***— ***VRS, ionosphere, levelling process, total electron content (TEC), GPS***

## 1.0 Introduction

Total Electron Content (TEC) especially at equatorial region has been a great challenge to the researchers due to large anomaly. Extensive research need to be done in order to accurately model the ionospheric behavior. As for the study of Malaysia area, more data should analyzed in order to comprehensively map the ionospheric TEC especially using Virtual Reference station (VRS) data. VRS has become most popular solution in network RTK which symbolizes the new stage of precise Global Positioning System (GPS) positioning. Many research group in several countries such as Japan, Germany, Italy, and Singapore done their research in VRS concept, algorithm, performance, accuracy and method of transmitting the correction to the rover [1][2][3].

In Malaysia, ionospheric studies for VRS are still new especially in the monitoring activity on TEC. The ionosphere in Malaysia is unique because of her location near the equator, where a lot of phenomena such as the equatorial anomaly and fountain effect make it good for studies [4]. The ionosphere also is the major contributor of errors in GPS, especially during the 11-year sunspot cycle [5]. The incoming 11-year sunspot cycle is expected to peak in 2013. The ionosphere condition is distinctly severe during ionospheric disturbances caused by high solar activity, which raises the question of how will this affect. The ionosphere in the equatorial region, especially Malaysia. This cycle's peak, which is called solar maximum, is expected in May 2013 [6]. During this stage, the mean TEC value is predicted to be increase.

VRS, developed by Trimble Terrasat is a common approach to overcome the core issue in network RTK which is modelling of errors, network ambiguity fixing, error interpolation and broadcasting the correction parameters [7]. The 4 steps in the generation of VRS are error modelling, network ambiguity fixing, reference data displacement and error (Correction) interpolation. VRS data from the reference station network is transferred to a computing center where the network data is used to compute models of ionospheric, tropospheric and orbit errors. The carrier phase ambiguities are fixed for the network baselines and the actual errors on the baselines are derived in centimetres (cm) accuracy using the fixed carrier phase observations.

MyRTK net is nation-wide GPS network and system infrastructure developed for GPS users to provide RTK and DPGS services. There are 78 permanent GPS refference station in MyRTKnet where 51 station located in peninsular Malaysia and remaining situated in Sabah and Sarawak [8]. The station tracks GPS signals and send them through dedicated data lines to a central server at DSMM Geodesy section, which manages and distributes GPS data to subscribers in real time. The network-RTK is able to serve multiple VRS users and provide these users with correction data for their surveys. MyRTKnet provides various levels of GPS correction and data and their use will depend on technique and application to be employed by the users.

In this paper, the focus is placed to study the concept of VRS techniques in Malaysia and the development of TEC calculation in ionospheric area using RINEX (Reciever Independent Exchange Format) VRS data format which received from JUPEM (Department of Survey and Mapping Malaysia) Kuala Lumpur. The data is from 15 reciever station on 28th April 2008.

## 2.0 Material And Methods

### 2.1 Data collection

Data collection is carried out using data from JUPEM. VRS station networks in a RINEX data format. The VRS data (RTK) consists of observation data and navigation data which dated on 28th April 2008, with 24 hours observation as per Table 1.

**Table 1** 15 Receiver station in Malaysian used in project

| No | Station ID | Latitude | Longlitude | Height |
|---|---|---|---|---|
| 1 | KUKP | 1.333275 | 103.45343 | 15.429 |
| 2 | BANT | 2.825956 | 101.53735 | 8.82 |
| 3 | UPMS | 2.993396 | 101.72351 | 100.385 |
| 4 | MERU | 3.138237 | 101.40746 | 6.433 |
| 5 | AYER | 5.750245 | 101.86015 | 67.3 |
| 6 | TGPG | 1.367411 | 104.10826 | 18.107 |
| 7 | UTMJ | 1.565815 | 103.63956 | 80.44 |
| 8 | KTPK | 3.170944 | 101.71761 | 99.79 |
| 9 | KUAN | 3.834378 | 103.35035 | 25.426 |
| 10 | IPOH | 4.588471 | 101.12618 | 41.854 |
| 11 | BKPL | 5.338986 | 100.21836 | -0.062 |
| 12 | USMP | 5.357788 | 100.30404 | 19.907 |
| 13 | RTPJ | 6.003363 | 101.99147 | 23.948 |
| 14 | GETI | 6.226192 | 102.10546 | -0.477 |
| 15 | ARAU | 6.450158 | 100.27974 | 18.078 |

The GPS data from satellites include ephemeris data in signals they transmit to VRS receiver location. Ephemeris data is a set of parameter that can be used to accurately calculate the location of a GPS satellite at particular point of time. Measurements can be done at centimetre-level with the VRS concept if certain factors are taken into account as shown at Figure 1.

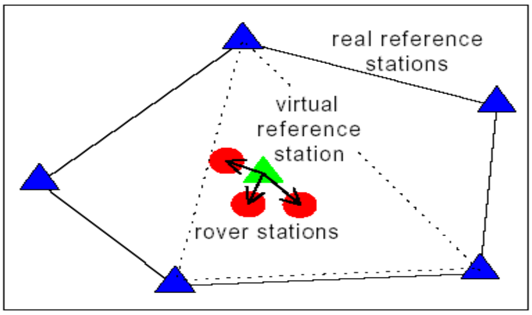


Figure 1: Virtual GPS reference station in a regional network [9].

## 2.2 Total Electron Content (TEC)

Total electron content (TEC) is an important descriptive quantity for the ionosphere of the Earth. TEC is the total number of electrons present along a path between two points, with units of electrons per square meter, where 1016 electrons/m² = 1 TEC unit (TECU). TEC is also a key parameter not only for ionospheric studies but also for the correction of ionospheric effects which degrade GNSS positioning accuracy. TEC is significant in determining the scintillation and group delay of a radio wave through a medium. Ionospheric TEC is characterized by observing carrier phase delays of received radio signals transmitted from satellites located above the ionosphere, often using GPS satellites [10].

The process of extracting data from RINEX file is done by using the Matlab programming language whereby the RINEX file is obtained from the GPS receiver as shown in Figure 2. The programme will analyse and extract the information needed in calculating the TEC from the observation and navigation RINEX file. The results will be depicted in the graphs of elevation angle, different phase, different delay, TECs and TECv versus time.

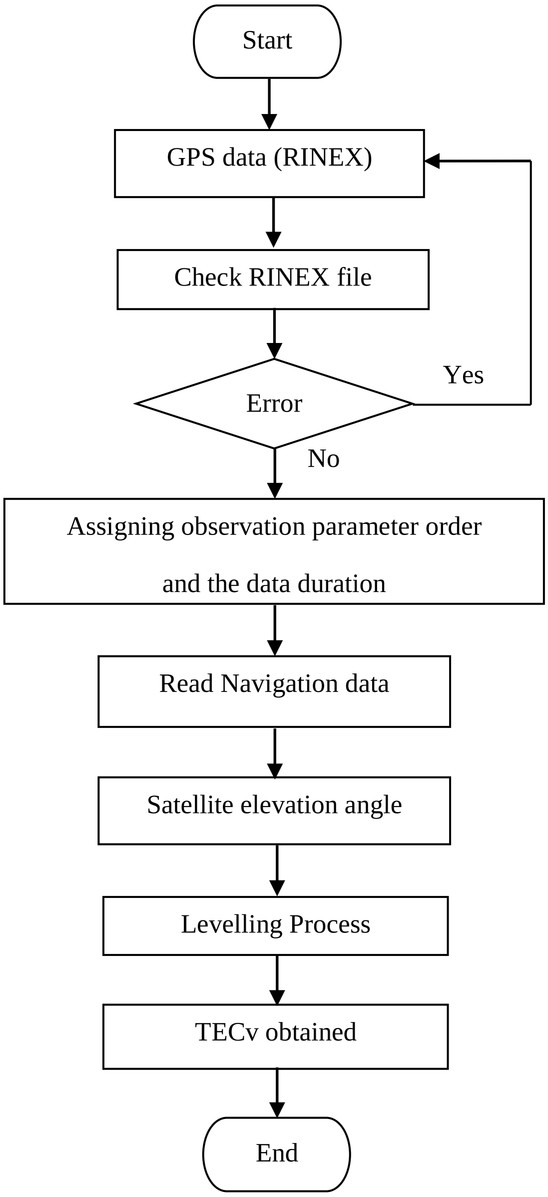


Figure 2: Flowchart of TEC processing

There are several methods to obtain the TEC over the reference station. In this study, the TEC can be obtained from the IGS TEC map and from dual frequency method with different accuracy. The TEC measurements obtained from dual frequency VRS receivers are one of the methods of investigating the earth's ionosphere.

The electron density in the ionosphere varies with geographic latitude, season, solar cycle and time of day. During quiet solar activity, the daytime maximum TEC occurs around noon and past noon local time while the minimum TEC occurrence is post midnight. A dual frequency VRS receiver measures pseudoranges and carrier phases at L1 (1575.42 MHz) and L2 (1227.60 MHz) and its observables are used to compute TEC. The differential time delay measurements are used to remove the ambiguity term.

A GPS operates on 2 different frequency f1 and f2 which a derived with a fundamental frequency (fo) of 10.23MHz. (f1 = 154fo, f2 = 120fo). These carrier frequencies contain codes modulation so that by comparing them to the reference code and we can measure the travelling time of the codes and the carrier between the satellite and the receiver. A dual-frequency GPS receiver measures the difference in ionospheric delay between the L1 and L2 signal. The group delay for dual-frequency GPS receiver can be written as:

$$P_2 - P_1 = 40.3TEC\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right) \quad (1)$$

where, $P_1$ and $P_2$ are the group path lengths, $f_1$ and $f_2$ are the corresponding high and low GPS frequency respectively. From (1), TEC can also be obtained by writing as:

$$TEC = \frac{1}{40.3}\left[\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right]\left(P_2 - P_1\right) \quad (2)$$

The TEC data derived from pseudorange measurement contained large noise level as compare to the carrier phase measurement. In order to reduce the noise effect, pseudorange data is smoothed by using carrier phase measurement technique known as carrier phase leveling  written as (3).

$$B = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\{(P_{1i} - P_{2i}) - (L_{2i} - L_{1i} \quad (3)$$

where:

N = number of measurement in a phase-connected arc of data.,

P1i = Pseudorange delay for f1,

P2i = Pseudorange delay for f2,

L1i = Phase delay for f1, and

L2i = Phase delay for f2

The leveling bias, B is computed to minimize the root-sum-square difference between pseudorange and phase differential delay. The TEC observable for measurement i is the carrier phase difference added to the bias B. After bias adjustment, the root-mean-square difference between the pseudorange and earlier phase delays is dominated by pseudorange noise

## 2.3 Parameters of the study

**Slant TEC:** The Slant TEC (TECs) is a measure of the total electron content of the ionosphere along the ray path from the satellite to the receiver. It can be calculated by using pseudorange and carrier phase measurements as in Eq. (2). As slant TEC is a quantity which is dependent on the ray path geometry through the ionosphere GPS receiver, the user can easily obtain both the absolute TEC and its rate of change.

**Vertical TEC:** The vertical TEC (TECv) is the main interest in the ionosphere research. Therefore, the TECs obtained from VRS observable are converted to vertical using a suitable mapping function. However this conversion introduces a few errors in the middle latitude where electron density is small. But it may result in obvious errors at low latitude with large electron density and great gradient [11]. In order to refer to the vertical TEC, the single layer thin-shell model was employed to determine the absolute vertical TEC (TECv).

**Mapping functions:** TEC measurement is based on assumption that ionosphere is a spherical shell at fixed height given by the center of mass of the ionospheric profile at 600 km above the earth's surface. A vertical TEC is obtained by converting the slant TEC using a correction factor base on zenith angle at the Ionospheric Pierce Point (IPP), which is the intersection of the user line of sight to the tracked satellite. The slant TEC is related to vertical TEC by an obliquity factor χ as follows:

$$TEC_V = TEC_S\left(\cos\chi'\right) \tag{4}$$

The single layer mapping (SLM) function can be written as:

$$F(\chi) = \frac{TEC(\chi)}{TEC(0)} = \frac{1}{\cos\chi'\left(or\sin\beta'\right)} = \frac{1}{\sqrt{1-\sin^2\chi'}} \tag{5}$$

where:

$$Sin\chi' = \frac{R_E}{\left(R_E + hm\right)}\sin\chi \tag{6}$$

$R_E$ = the mean earth radius

hm = the height of a maximum electron density, and χ and χ' = the zenith angles at the receivers site and at the ionospheric pierce point IPP, with value of Re is typically set to 6371 km and hm is at 350 km. The mapping function below is modified single layer model, M-SLM which is defined as:

with

$$\sin\chi' = \frac{R_E}{R_E + h_m}\sin(a\chi) \tag{7}$$

where $a$ is correction factor which is close to unity.

## 3.0 Result and Discussions

The following description showed the result of the MATLAB simulation for calculating TEC values, determining from the evaluation angle, calculating differential in code and phase delay, computing slant TEC and mapping using SLM function.

### 3.1 Levelling process

Figure 3 to 5 show the evaluation angle for BANT (PRN28), KUKP (PRN25) and AYER (PRN10). The elevation angle was determined at BANT station at 1:00- 2:00 UTC is 49º and 22º while at KUKP from 52º to 23º and at AYER is between 43º and 67º

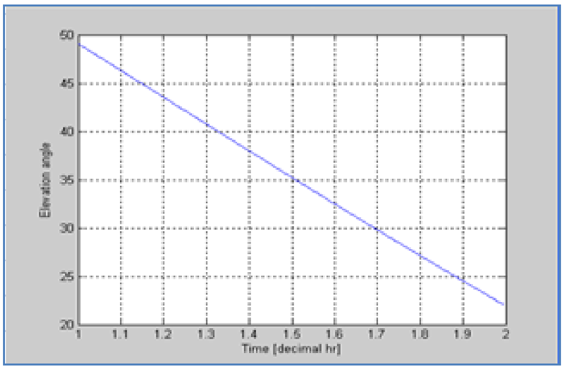


Figure 3: Evaluation angles for PRN28, 1:00 – 2:00 UT at BANT (Banting)

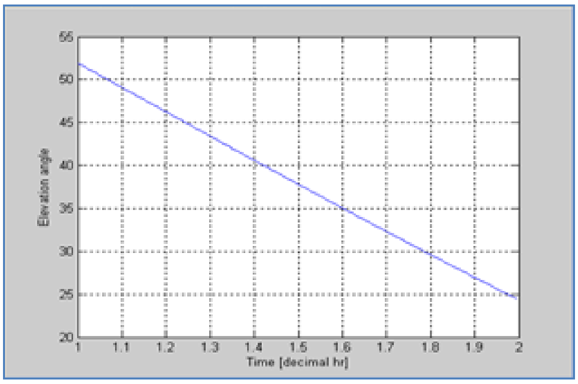


Figure 4 : Evaluation angles for PRN25, 1:00 – 2:00 UT at KUKP (Kukup)

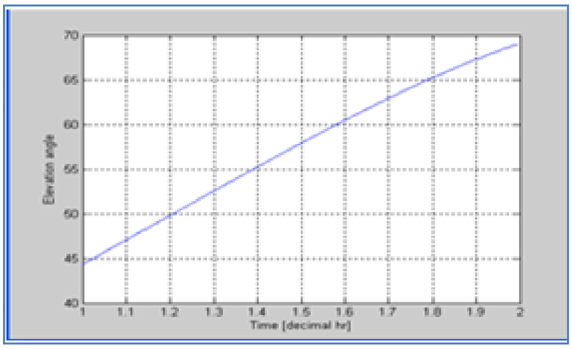


Figure 5 : Evaluation angles for PRN10, 1:00 – 2:00 UT at AYER (Ayer Lanas)

Figures 6 to 8 show the differential code and differential phase before scaling. The difference in code measurement (P2-C1) and difference in phase measurement (L1-L2) were calculated. The differential delay from the code measurements was very noisy as compared to the differential phase measurement. The phase measurements however are ambiguous which means slant delays have been derived by the phase. This will eliminate the integer ambiguity.

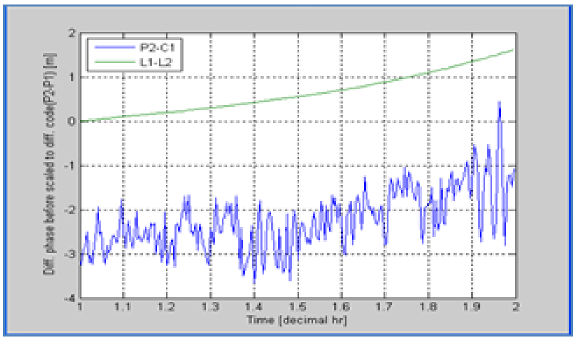


Figure 6 : Differential phase (L1-L2) and differential code (P2-C1) for PRN28, 1:00-2:00 UT at BANT

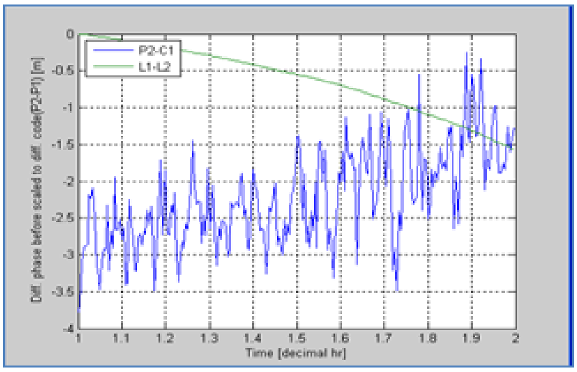


Figure 7 : Differential phase (L1-L2) and differential code (P2-C1) for PRN25, 1:00-2:00 UT at KUKP

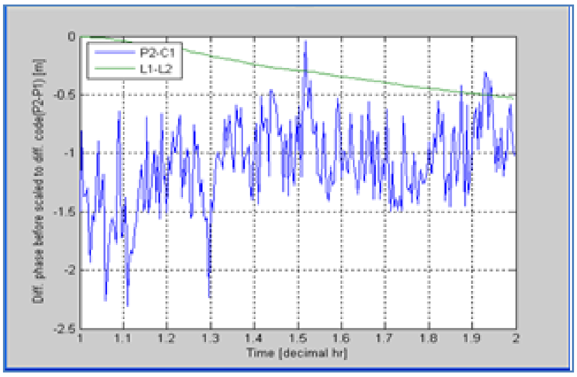


Figure 8 : Differential phase (L1-L2) and differential code (P2-C1) for PRN10, 1:00-2:00 UT at AYER

The shifted values between differential code and phase were calculated. The difference value then added to the relative phase. Differential carrier phase then converted to absolute scale by fitting it to the differential group delay as shown in Figure 9 to 11. According to the Figures 9 to 11, the code TEC displayed here has been smoothed by phase TEC. The smoothed code TEC estimates that shows noise and multipath fluctuations. Elimination of the code multipath effect normally can be seen at both ends of the path, can be done by fit the code differential delay at the higher elevation angles as references. This is called levelling process where it applied to reduce carrier-phase ambiguities from the data.

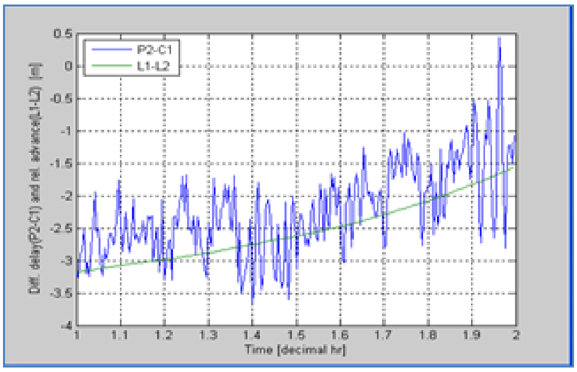


Figure 9 : Relative range error computed from the differential carrier phase advance for PRN 28, 1:00-2:00 UT at BANT.

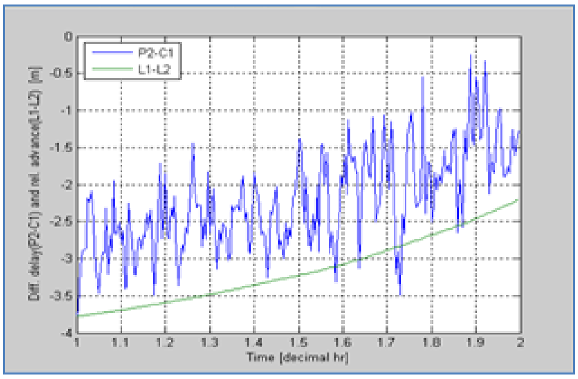


Figure 10 : Relative range error computed from the differential carrier phase advance for PRN 25, 1:00-2:00 UT at KUKP.

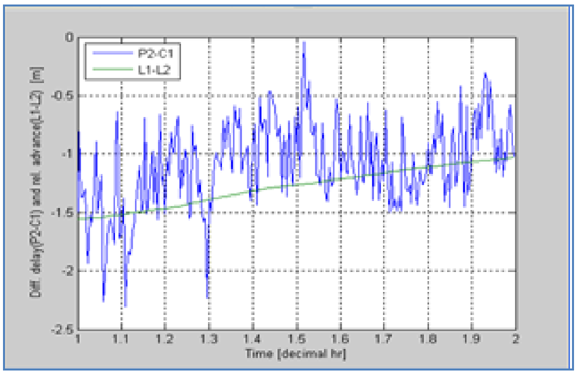


Figure 11: Relative range error computed from the differential carrier phase advance for PRN 10, 1:00-2:00 UT at AYER.

Slant TEC are calculated by multiplying smoothed differential delay with a constant as shown in equation (2). Results of the slant TEC are plotted in Figure 12 to 14.

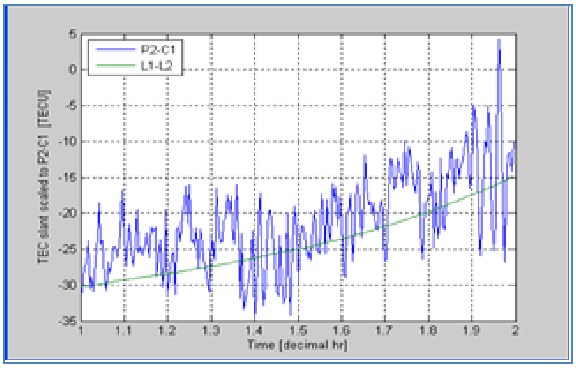


Figure 12: TEC Slant scale to (P2-C1) for PRN 28, 1:00-2:00 UT at BANT.

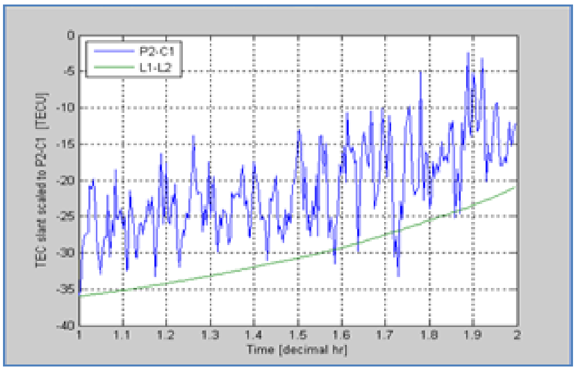


Figure 13 : TEC Slant scale to (P2-C1) for PRN 25, 1:00-2:00 UT at KUKP.

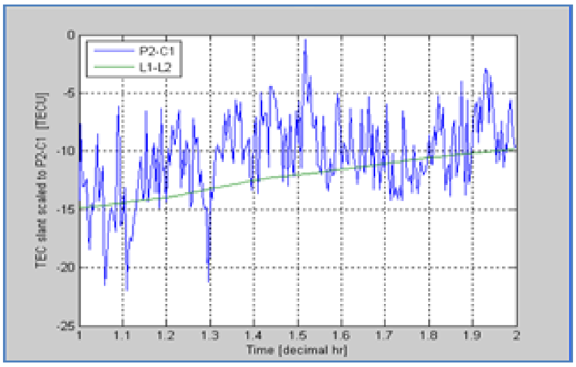


Figure 14 :TEC Slant scale to (P2-C1) for PRN 10, 1:00-2:00 UT at AYER.

A Single Layer Mapping (SLM) function was used to convert slant TEC to vertical TEC using equations described in (2) to (4). Figure 15 to 17 shows the result of converting slant TEC to vertical TEC. The analysis at an equatorial region used SLM mapping function where the peak altitude ranges at 350 km. The vertical TEC values are precise, accurate and without multipath, unless the multipath environment is really terrible, in which case a small, residual amount of multipath can even be seen in the differential carrier phase. The total electron using dual frequency for BANT station is -24 TECU to -7 TECU, KUKP station is at -29 TECU to -11 TECU while AYER station starts at -11 TECU to -9.2 TECU.

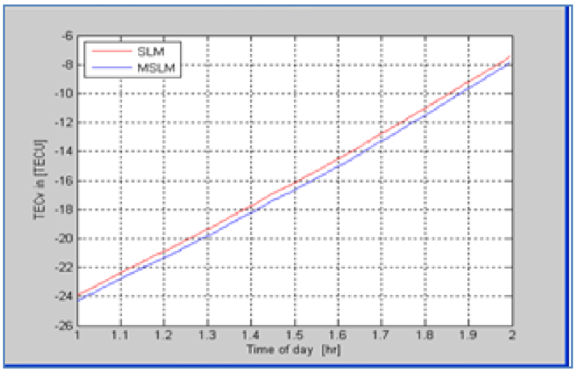


Figure 15 : Vertical TEC for PRN 28 1:00-2:00 UT at BANT station.

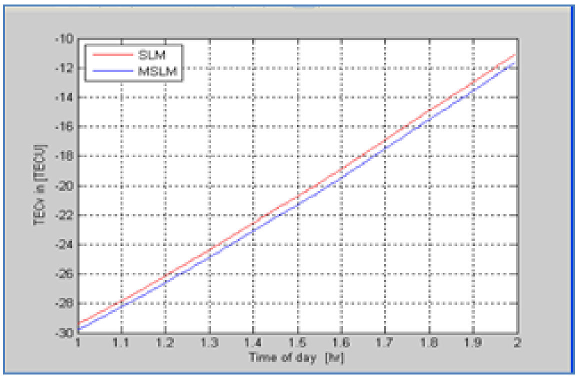


Figure 16 : Vertical TEC for PRN 25 1:00-2:00 UT at KUKP station.

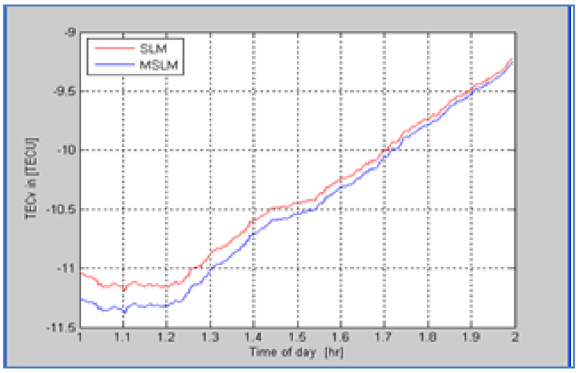


Figure 17 : Vertical TEC for PRN 10 1:00-2:00 UT at AYER station.

### 3.2 TEC Calculation based on time of the day and location

Based on time of the day, data for each time intervals we processed, and the result for Table 2 where it is combination selected station between day time (morning), evening time and also night time. The time categorized is from 1 am (morning) 6pm (evening) and 8pm (night). For the 3 daily time observation the range error varied from -1.05 metres to -3.3 metres in morning time, -3.1 metres to -3.8 metres in evening time and -

4.15 metres to -5.35 in night time. TEC is less in morning time which TEC averagely -14.7 TECU and night time which is around -21.6. The highest TEC was found during evening time which TEC averagely at -33.9 TECU.

From the Table 2, it also shown the the station which located at east area (AYER) has the less TEC value compared to station in central area and south area. The south area (KUKP) however contains the most TEC on the day measured.

**Table 2** Selected VRS station and results

| | Morning (PRN23) | | Evening (PRN25) | | Night (PRN11) | |
|---|---|---|---|---|---|---|
| Station | MEAN TEC VALUE (TECU) | Range Error (Meter) | MEAN TEC VALUE (TECU) | Range Error (Meter) | MEAN TEC VALUE (TECU) | Range Error (Meter) |
| KUKP | -20.5831 | -3.3 | -32.4763 | -5.1 | -22.3289 | -3.65 |
| AYER | -10.4657 | -1.05 | -28.9432 | -4.6 | -17.9641 | -3.6 |
| BANT | -16.0104 | -2.5 | -32.3704 | -5.15 | -22.4921 | -3.1 |
| UPMS | -14.7066 | -2.3 | -26.2375 | -4.15 | -23.1543 | -3.5 |
| MERU | -17.1469 | -2.75 | -33.9636 | -5.35 | -24.5498 | -3.8 |

3.3 TEC Calculation based on ionosphere height

Based on Figure 18 below shows that the data is taken from KUKP station and the mean TEC in this station is increased from 100km from the station to the maximum 600km.

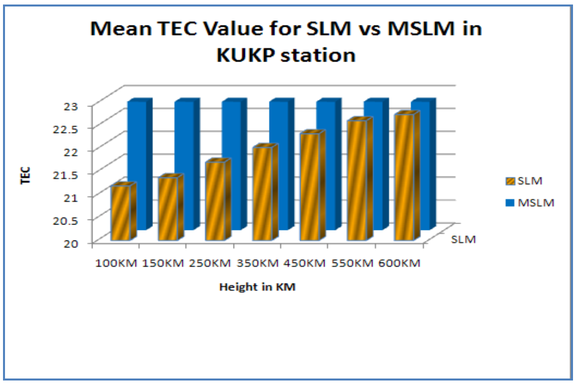


Figure 18 : Mean TEC value SLM vs MSLM in KUKP station

From the result Table 3, it shows that the mean TECU increase from height 100km is at -21.1897 TECU and it increased to -22.7473 at the end of height 600 km

However, in Figure 19, the cummulative difference between SLM and MSLM dropped at the height of 350 km to end of 600 km height. It also learned from the graph where the TEC looked stable on the TEC increased at height 350 km. This is where the value of height is taken for the studies since TEC begins to stabilize in its uniformity and the value does not change much at the next heights [12].

**Table 3** SLM vs MSLM in KUKP station

| KUKP | 100KM | 150KM | 250KM | 350KM | 450KM | 550KM | 600KM |
|---|---|---|---|---|---|---|---|
| SLM | 21.1897 | 21.3686 | 21.7091 | 22.0286 | 22.3289 | 22.6119 | 22.7473 |
| MSLM | 22.8012 | 22.8012 | 22.8012 | 22.8012 | 22.8012 | 22.8012 | 22.8012 |
| DIFF | 1.6115 | 1.4326 | 1.0921 | 0.7726 | 0.4723 | 0.1893 | 0.0539 |
| CUMM increase | 0 | 0.784608 | 1.493342 | 1.401242 | 1.317036 | 1.241163 | 0.593828 |

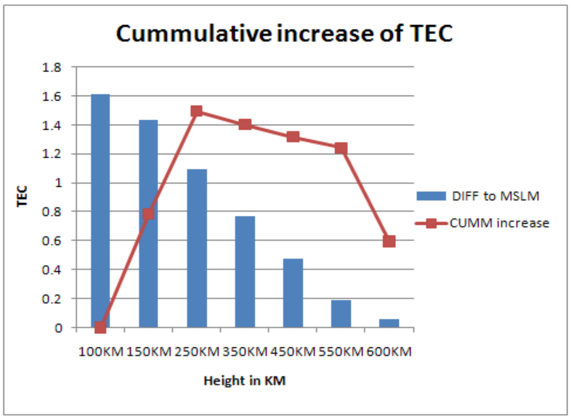


Figure 19 : SLM vs MSLM in KUKP station

## 4.0 Conclusions

In this paper, the aim is to determine and implement the levelling process technique use in dual-frequency GPS signal to calculate TEC and to estimate positioning error from this TEC value. In this technique, the carrier phase ambiguity from the data is reduced by assessing the error translated from code-delay to carrier-phase. The result shows that at different latitudes and longitudes within Peninsular Malaysia where latitudes are ranging from 1º 19' 59.8"N to 5º 45' 0.89"N and longitudes varies from 101º 24' 26.8"E to 101º 51' 36.5"E

The TEC total in this data which has been taken in 28$^{th}$ April 2008 was range from -14.7006 TECU to maximum -33.9636 TECU (or 14.7006 to 33.9636 TECU). From the result itself it shows that the range of TEC is significantly matched to the Sunspot Number prediction from NASA where it predicted the total minimum and maximum TEC in January-May 2008 is around 0.092 to 33.083 TECU [13]

It also learned that the TEC pattern between height of station to ionosphere increased from 100 km to the maximum 600 km ionosphere layer(F region). However the cumulative increased to the MSLM have been dropped and stabilized from 350km and above and it almost matched the degree of ionozation measured by High Frequency Active Auroral Research Program (HAARP) which has been shown in Figure 1 early of this paper [14].

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